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CHARACTERIZATION OF LIQUID CRYSTAL DISPLAYS FOR OPTICAL SIGNAL PROCESSING APPLICATIONS

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IN-HOUSE TECHNICAL REPORT

CHARACTERIZATION OF LIQUID CRYSTAL DISPLAYS FOR OPTICAL SIGNAL PROCESSING APPLICATIONS

Ms. Denise Blanchard and 1Lt. Michael Ward

ABSTRACT

Characterization and analysis of the liquid crystal displays (LCD) used in liquid crystal televisions for possible use as economical spatial light modulators has been performed. This paper presents results of Photonics Center research into LCDs with recommendations for possible applications. This study measured pixel array dimensions; transmission as a function of wavelength, bias voltage, and video voltage; modulation depth as a function of bias voltage; response time; and the optical losses and phase distortion of the LCD. We discuss the usefulness of the LCD as a variable attenuator and as an adaptive wavefront compensator, and our ongoing efforts to use the device as a 1-D spatial light modulator in an optical signal processing system.

I. INTRODUCTION

In the development of analog optical signal processing systems, a device is needed for impressing information into one- and two-dimensional optical data fields. These multi-element fields enable full utilization of the speed inherent in the massive parallelism of optics. A category of devices called spatial light modulators (SLMs) fulfills this task. SLMs spatially modify the amplitude, phase, or polarity of an incident signal of coherent or incoherent light.

Several types of spatial light modulators (liquid crystal light valves and magneto-optic SLMs for example) operate at suitable performance levels for some optical processing functions, but are typically not cost efficient. From a cost standpoint, a $100 liquid crystal television may prove useful in the capacity of an SLM. Thus, it is advantageous for the Air Force to examine the characteristics and possible applications of this device.

This paper briefly outlines the operating principles of the LCD and describes our device configuration. It then reports our findings with regards to pixel array dimensions; transmission as a function of wavelength, bias voltage, and input video voltage; modulation depth as a function of bias voltage; response time; total optical losses due to reflection, scattering, and absorption; and phase distortion of the LCD. Finally, based on these measurements, we make recommendations concerning the application of the LCD to optical processing systems.

II. LCD Operating Principles

The LCD consists of a matrix of liquid crystal cells sandwiched between two glass plates with transparent electrodes, two polarizing sheets with parallel polarization axes, and two plastic diffusers, as in Figure 1. The inside surfaces of the glass plates have fine grooves which run along one direction, with the grooves on one plate running perpendicular to the grooves on the other.

The linear liquid crystal molecules adhere to these grooves, aligning themselves parallel to the groove direction. The net result is a 90 degree rotation of molecular orientation from one glass face to the other; this is called the twisted nematic effect.

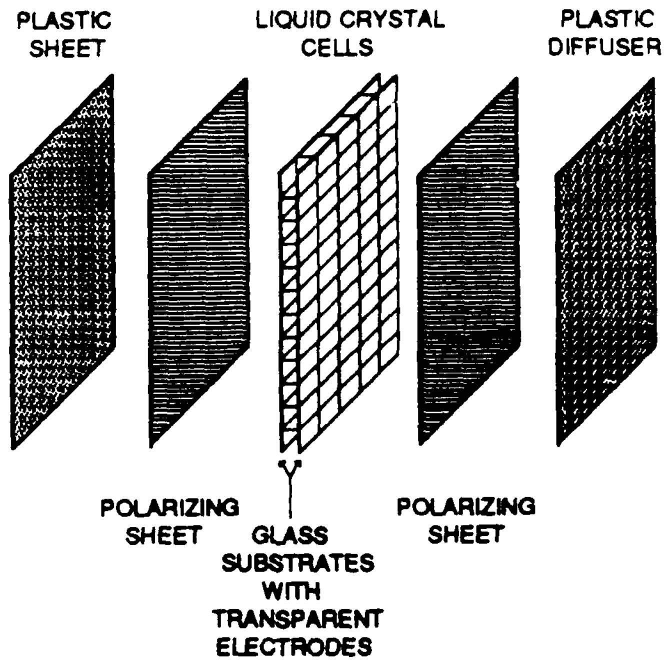


Figure 1. Structure of the Liquid Crystal Television

Light is linearly polarized by the first polarizer and enters the liquid crystal. With zero voltage between the plates, the helical twisting of the liquid crystal molecular orientation causes the light to exit the second glass plate polarized at right angles to its initial polarization. The analyzer (second polarizer) then prevents this radiation from passing.

With the appropriate voltage between the plates, the cells of liquid crystal molecules have a bias voltage applied to them. This rotates the polarization of the emerging radiation so that it is no longer aligned perpendicular to the direction of the analyzer, thus some light passes through. The amplitude of the transmitted light is given by

$$E_0 = E_1 \cos \theta$$

where: E_0 = the amplitude out of the analyzer
E_1 = the amplitude into the analzer
θ = the angle between the polarization axis of the analyzer and the polarization direction of the light.

Since the polarization direction of the light is related to the bias voltage, modulating the voltage varies the transmission of the device by changing θ.

III. Apparatus

The LCD device that we use is the screen of a Radio Shack model 16156 Liquid Crystal Television. It was prepared by :

1) Removing the plastic diffusers.
2) Peeling the polarizing sheets from the glass substrates.
3) Breaking the lid hinge and securing the liquid crystal array in an upright position.

Video may be impressed onto the LCD via several methods. We may directly display the output of a closed circuit video camera. Another method utilizes a personal computer to write video patterns on the LCD. Finally, we may record the video image with a still video recorder on a diskette, and display the recorded image on the LCD. The still video recorder was used as the input to the LCD through most of our experiments. This method was chosen because once an image is stored on a diskette it can be easily regenerated. This property was very useful when we wanted to verify our results by repeating an experimental procedure.

IV. Experimental Results

A. Pixel Array Dimensions

The LCD that we have investigated has a 7.3 cm by 5.6 cm screen. The screen is a uniform 2-D grid of raster-scanned liquid crystal pixels, with each pixel capable of modulating light transmitted through it. The LCD has a resolution of 162 horizontal elements by 149 vertical elements. The pixels were observed and measured with a calibrated scale under a microscope. Each pixel has rectangular dimensions of 435 µm x 360 µm with a spacing of 30 µm between each pixel. Previous studies [1,2,3,4] used LCD models with square pixels, approximately 350 µm on a side. Figure 2 shows a 3 pixel by 4 pixel section of the screen, at a magnification of 45 times its actual size.

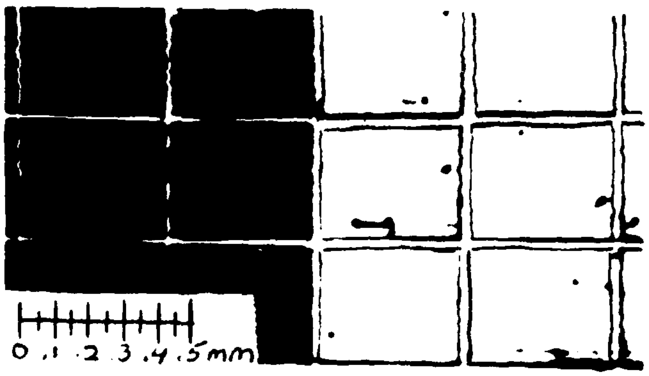


Figure 2: A magnified view of a 3x4 array of pixels. The left half recieved a black video signal and the right half recived a white video signal.

B. Transmission as a Function of Wavelength and Bias Voltage

Transmission of light through the LCD is an important design criterion. When the LCD is used as a spatial light modulator in an optical processing system the transmission characteristics will be a primary determinant of the power and wavelength required of the source and required detector sensitivity. In this section we discuss our measurement of LCD transmission as a function of three discrete wavelengths and as a function of bias voltage. The next section describes transmission as a function of input video voltage.

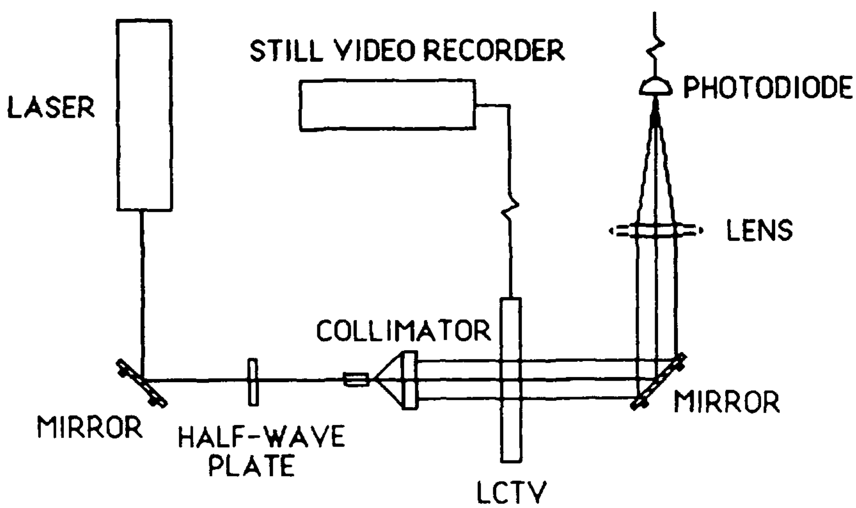


Figure 3: The experimental set up used for the measurement of transmission as a function of wavelength, bias voltage and video voltage.

The measurement was performed with the apparatus shown in Figure 3. The beam of a tunable HeNe laser (polarized at 500:1) passed through a 1/2 waveplate, which rotated the polarization direction of the beam to match the alignment of one of the birefringent axes of the LCD. (For a description of the birefringent effect and how it affects LCD transmission, see Appendix.) The beam was then expanded and collimated. Before the beam impinged on the screen, an iris aperture reduced its diameter to 5 cm so as not to overfill the optics that followed. A still video recorder input video images to the LCD, which was mounted to permit translation in the vertical and horizontal directions. The polarization orientation of the radiation which emerged from the LCD was determined by the applied voltage. The analyzing polarizer blocked all light except that which was oriented parallel to its own polarization axis.

The light transmission characteristics of the LCD are dependent upon the bias voltage applied to each pixel. The value of this voltage was measured across the center contact of the brightness control potentiometer and a grounded test point, determined from the Liquid Crystal Television Service Manual[5]. The voltage varied with the brightness control on the television over a range of 13 to 19 Volts.

Figure 4 displays LCD transmission as a function of bias voltage at three of the output wavelengths of the tunable HeNe laser. The transmission is expressed as a percentage of the power incident on the LCD and is shown to be an increasing function of bias voltage. The laser could be tuned to emit at four wavelengths: 632.8nm (red), 611.9nm (orange), 594.1nm (yellow), and 543.0nm (green.) However, due to the low output power of the green laser line (< 3.6μW), the transmitted power of this HeNe wavelength was in the noise level of the detector, and hence the transmission results at 543.0nm were omitted from Figure 4.

The transmission at 632.8 nm varies from 0.2 % at the low end of the voltage scale to a high of 35.5 % at a bias voltage of 19 Volts. The transmission response also appeared to be slightly more linear over the voltage range at this wavelength. The next most efficient transmission wavelength occurred at 611.9 nm with a transmission peak of 32 %. The 594.1 nm line peaked at a transmission of 26.5 %. The red laser line (632.8 nm) is used throughout the rest of this experiment because of the slightly higher transmission of the LCD at this wavelength.

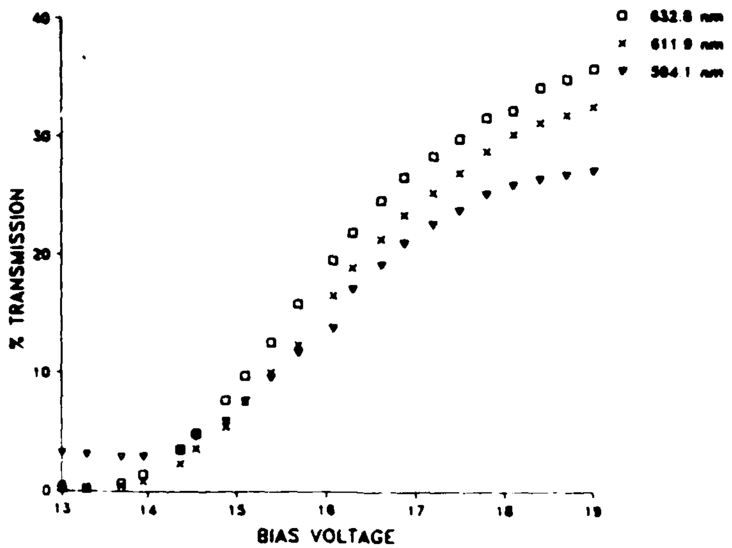


Figure 4: Transmission as a function of wavelength and bias voltage.

C. Transmission as a Function of Input Video Voltage

Starting with the same configuration as in Figure 3, we replaced the still video recorder input with a microprocessor to create grey scale values. The microprocessor was limited to generating 13 discrete video voltages in the range of 0.6 volts to 2.5 volts, measured peak to peak on an oscilloscope trace of the video output. These video voltages corresponded to grey values on the microprocessor screen with a black screen at 0.6 volts and a white screen at 2.5 volts. The transmission was measured at each of 13 discrete video voltages with the bias voltage set at a constant value of 14.61 volts for best contrast. (See following section for discussion of how best contrast was determined.) The results are shown in Figure 5.

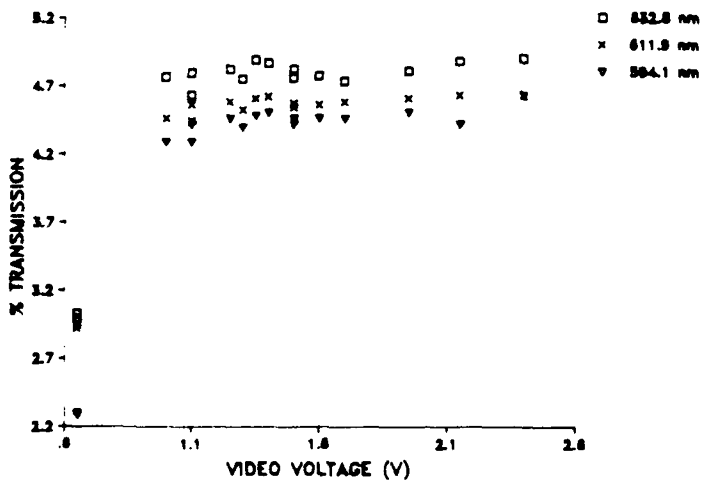


Figure 5: Transmission as a function of input video voltage, at a bias voltage setting of 14.61 volts.

The data in this figure indicates that the for input video voltage levels obtainable with the microprocessor, LCD transmission is very nearly a step function with minimum transmission for a video voltage of 0.6 volts and maximum transmission at larger voltages. This indicates that if we vary only the video voltage, we can reliably expect to find no more than two distinct grey levels. Later we will describe a method whereby we increase the effective number of grey levels of the LCD. Briefly stated, this method allows the number of "on" pixels in a column to represent a given numeric value. A cylindrical lens sums the light output from the "on" pixels in this column, and at the focal plane of the lens the total intensity is proportional to the numeric value.

D. Modulation Depth

Another interesting characteristic of the LCD is the contrast ratio. We express the contrast ratio in terms of the modulation depth (MD) which is defined as follows:

$$MD = (I_{MAX} - I_{MIN}) / (I_{MAX} + I_{MIN})$$

I_{MAX} is the measured intensity of light transmitted through the LCD when a video signal corresponding to a white screen is input through the video jack, and I_{MIN} is the measured intensity when a video signal corresponding to a black screen is input.

Using a television with manufacturer's polarizers, we measured the modulation depth over the full range of the bias voltage, from 13.3 - 19.4 Volts (see Figure 6). We found that the peak modulation depth, 0.91, for an LCD with manufacturer supplied polarizers far exceeded the peak value (0.45) for an LCD where the manufacturer's polarizers had been replaced with commercially available dichroic sheet polarizers. The quality of the manufacturer's polarizers was not tested because they are rendered unusable in the process of removing them from the glass substrates of the LCD. The peak modulation depth of 0.91 $\pm$ 0.04 was obtained at a bias voltage of 14.61 $\pm$ 0.01 Volts. This is the voltage setting at which contrast is maximized. The data also reveals that for voltages less than 13.94 Volts, the contrast becomes inverted, that is--the "black" screen transmits more light than the "white" screen. The peak inverted modulation depth is at 0.76 $\pm$ 0.07 at a bias voltage of 13.53 $\pm$ 0.01 Volts. We maximize the contrast by operating the LCD at the peak modulation depth.

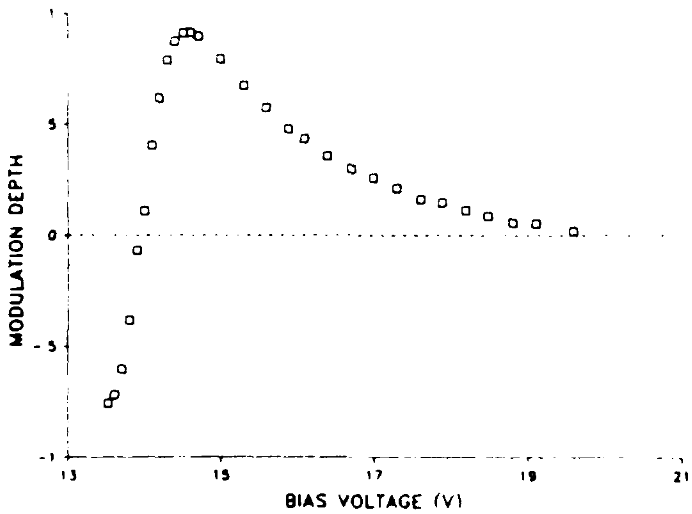


Figure 6: Modulation depth as a function of bias voltage.

E. Response Time

The liquid crystal screen receives video images in an interlaced scanning manner controlled by the television electronics. The first scan only addresses a field of even-numbered lines. Each line electrode is selectively driven by a pulse which has an approximate width[5] of 90 µsec. By itself this field would be a rather poorly defined image. However, the field of odd numbered lines is immediately addressed in a second scan. The second field is interlaced between the lines of the first. The two fields are each presented at a rate of 60 Hz, with a delay of a half a cycle (8.5msec) between them. The eye accepts these overlapping fields as one frame.

In television, the frame frequency is 30 Hz. In order to prevent flickering, the frame is captured and duplicated by the television electronics into fields which are applied to the screen at 60 Hz. In other words, each pixel is refreshed twice during each frame. The field rate of the LCD was observed using the set up shown in Figure 7. An unexpanded 632.8nm HeNe beam is incident onto a single LCD pixel. The pixel is either bright or dark, as determined by input from a micro-processor. After passing through the LCD, the beam is expanded slightly with a lens, to avoid saturating the detector.

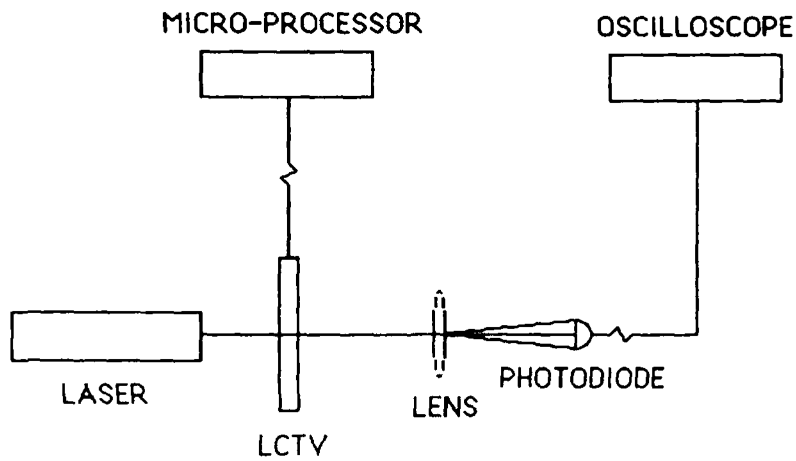


Figure 7: The experimental set up used to measure time response.

The optical detector used to detect the transmitted radiation has an analog output with a rise time (10% to 90%) of 1 msec. The combined effect of this rise time and the maximum pulse width of 90 µsec induced by the LCD's driving electronics could result in a total maximum delay of 1.09 msec on response time measurements.

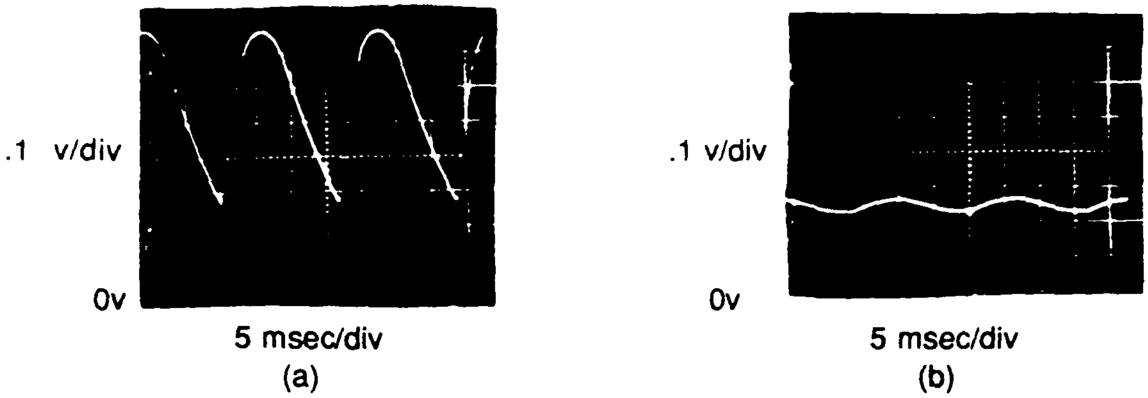


Figure 8: Transmission over time
a) of a bright pixel, b) of a dark pixel.

Oscilloscope traces of the photodetector output, shown in Figure 8, represent the variation of the transmission through a single pixel over time. Referring to Figure 8 (a), which represents the transmission through a bright pixel, it can be seen that 5 msec is required to obtain maximum transmission once a voltage field is applied to the pixel. *A maximum of 1.1 msec of this rise time results* from the electronics. The remaining delay can be attributed to the time required to achieve a complete re-orientation of the liquid crystal molecules.

Once the transmission achieves a maximum, the liquid crystal molecules begin to relax at a fairly constant rate until the next field is applied. Subtracting an approximate 1.1 msec delay due to the electronics, the remaining 10.9 msec decay time may be attributed to the liquid crystal material. During this relaxation, the liquid crystal permits a decreasing percentage of light to pass, without a voltage being applied. The fact that the pixel does not hold the high transmission value during the entire frame time, may have limited the number of unique gray values observed in section IV.C. If drive electronics were constructed to hold the pixel value constant during the entire frame time, a greater number of video levels could be achieved.[1]

The black "off" state of the dark pixel, refer to Figure 8 (b), corresponds to 0.22 volts. However, we see that the bright pixel, refer to Figure 8 (a), never relaxes completely to this "off" state. Since earlier the fall off of 10.9 msec was established to be limited by the liquid crystal material itself, we can assume that even if we could produce our own drive electronics, we could not expect to be able to switch this device any faster than 60 Hz.

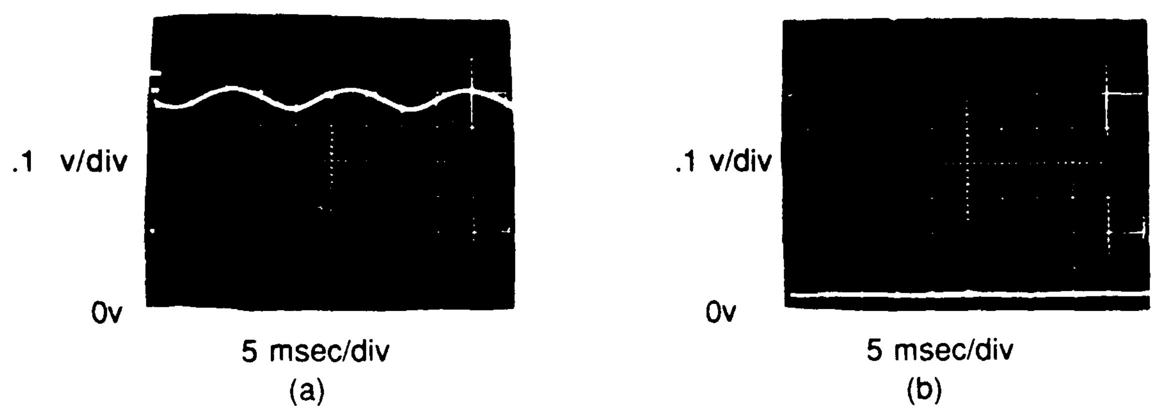


Figure 9: Transmission over time of a 2.5cm diameter area a) of a bright screen, b) of a dark screen.

In the applications discussed in this paper, we are interested in the average response over several pixels of the LCD. In order to observe the average response, we changed our setup by expanding and collimating our laser output. An iris was used to control the diameter of the beam incident on the LCD. Figure 9 shows the oscilloscope trace of the detector output of an incident beam of 2.5 cm diameter. Now the net effect of overlapping the two fields can be seen as a 60 Hz cycle with much less fluctuation in transmission than was seen with a single pixel.

F. Optical Losses

Optical losses due to specular reflection, scattering, and absorption were measured with the apparatus shown in Figure 10. The procedure described below was performed with an LCD in the "off" position without any input signal and stripped of the manufacturer's polarizers. The LCD was aligned perpendicular to the incident beam.

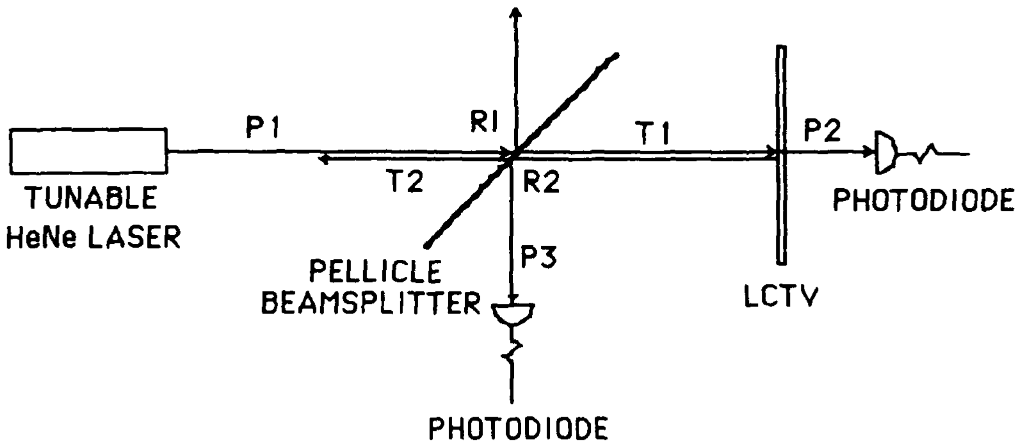


Figure10: The apparatus used to measure several optical parameters of the liquid crystal screen.

A laser beam with power P1 was incident onto a pellicle beam splitter. The power of the beam transmitted through the pellicle can be calculated since the reflection coefficients r1, r2, and the transmission coefficients t1, t2 were already measured. The beam passing directly through the pellicle then impinged on the LCD screen where the transmitted power P2 and the specularly reflected power P3 (compensated for losses at the pellicle) were measured.

The power transmitted (T=P2) through the LCD can be directly measured. The specularly reflected power (R) and power incident (I) on the LCD are easily computed using these relationships:

$$I=t1*P1$$

$$R=P3/r2$$

The difference I-(T+R) is attributed to optical losses such as scattering and absorption within the LCD. Therefore

$$L=I-T-R$$

The transmitted beam was found to be 68% of the power incident on the LCD, and specular reflection accounted for 15% of the same. Hence, using equation immediately above, the optical losses not due to specular reflection were calculated to be 17% of the incident power.

G. Interferometric Profile

Using a Zygo Mark IV interferometer, with a source wavelength of 830 nm, a contour plot of the LCD device, shown in Figure 11, was obtained. Over the entire area of the screen, we see a phase variation of approximately three wavelengths. Whether or not this magnitude of phase distortion permits the LCD to be used in phase sensitive processing is dependent upon the application.

However, we do see the LCD as a viable SLM for amplitude modulating applications, as detailed in the following section.

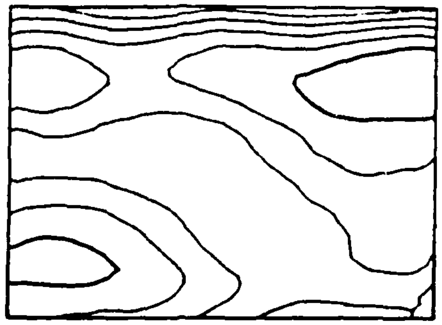


Figure 11: Contour plot constructed from a double-pass interferogram of the LCD. Each line represents a 0.45 wavelength variation at 830nm, hence the device shows approximately three wavelengths phase variation across its entire area.

V. Applications

The usefulness of the device in various applications will be examined in this section. Below we explain a suggested application for the device as a variable amplitude filter. We also include a brief description of our ongoing efforts to use a LCD as a 1 dimensional spatial light modulator in an optical adaptive signal processing architecture. Finally, the usefulness of an LCD device as an adaptive amplitude compensator is also discussed.

A. Use as a Variable Amplitude Filter

The LCD shows promise for use as a voltage controlled variable amplitude filter. Figure 4 presents the transmission of the device as a function of bias voltage. We see that over a range of 13 to 19 volts, the transmission varies continuously from approximately 0.2% to 30%.

Optical density (OD) is a standard measure of the attenuation of a neutral density filter:

$$OD = LOG_{10} (1 / T)$$

where T is the transmittance. Hence the OD of an LCD can be continuously varied from 0.5 to at least 2.7. The LCD has an area of 40.9 cm^2. A commercially produced variable filter with the same area and OD range costs upwards of $800. Hence, the LCD can serve as an economic alternative to commercially available variable filters, with the added advantage of being voltage controlled.

However, as Figure 4 shows, the LCD transmission demonstrates a slight dependence on wavelength. Hence, it is not truly a neutral density filter. But for a monochromatic system, the LCD should prove entirely suitable as a variable filter.

B. Use as a One Dimensional Spatial Light Modulator

One application of interest is to use the LCD as a low cost spatial light modulator (SLM). Previous studies have described its use in two dimensional signal processing. However, as seen in Figure 5, the pixels behave in a binary manner, with a distinct "black" value, a distinct "white" value, and very little else between these extremes. This severely limits the values that can be impressed upon the light as it passes through the device.

Here we describe a method using the LCD as a one-dimensional SLM and the application of such a device to an optical processing architecture[6]. In order to perform as a one dimensional SLM, a device must be able to selectively attenuate input light across a linear axis. Each point on this axis corresponds to a distinct intensity value.

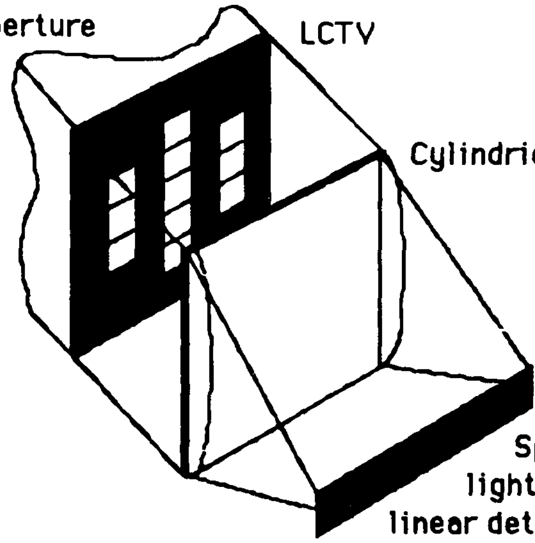


Figure 12: Experimental setup of the LCD as a one dimensional SLM

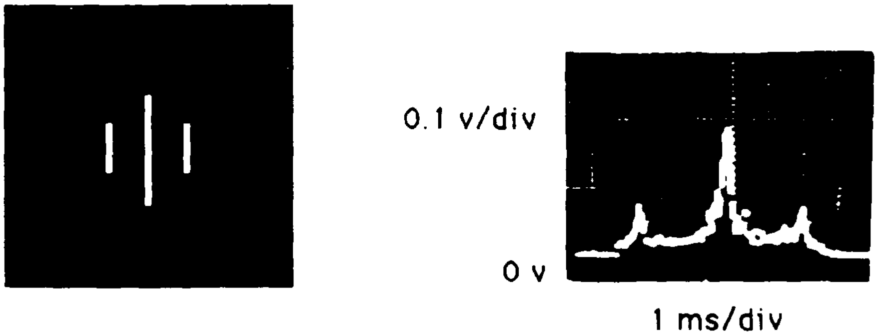
The weight value at a given location along the horizontal axis of the LCD is represented by a proportional number of "on" pixels. A cylindrical lens performs a summation in the vertical direction of the transmitted intensity. The intensity at a given location along the horizontal axis at the focal point of the lens is proportional to the weight at that same location. In this manner, the LCD acts as a one dimensional SLM with a maximum dynamic range limited by the number of pixels in a column. This concept is illustrated in Figure 12.

We currently use the LCD as a one dimensional SLM in an adaptive optical signal processing architecture. The system is being developed for adaptive noise cancellation and operates by correlating delayed versions of a jamming signal with the signal received by a primary antenna. Each delayed version of the noise must be weighted in order for the cancellation to occur. The LCD is used to impress these weights onto the light signal.

As a test of this system, a sample weight pattern was generated by a microprocessor in CGA graphics mode (a total of 320 horizontal pixels and 200 vertical pixels for the entire computer screen). A collimated HeNe beam was modulated by this pattern and summed in the vertical direction by a cylindrical lens. A linear detector array was located at the focal plane of the lens thereby permitting a direct observation of the intensity distribution.

The sample weight pattern is an area of 8X84 "on" pixels, flanked by two smaller patterns, both with areas of 8X28 "on" pixels. The spacing between the bars is 36 pixels. As mentioned earlier,the LCD has only 162 horizontal pixels and 149 vertical pixels for its entire screen. Therefore, the sample weight pattern is represented by one bar of 4X63 "on" pixels and two of 4X21 "on" pixels, spaced at 18 pixels from one another. The size ratio between the large and smaller bars is 3:1.

Figure 13(b) shows the oscilloscope trace of the detector output. One can see that the height of the large peak is nearly 3 times the height of the smaller peaks. The horizontal positions of the peaks correspond to the positions of the patterns on the screen. We are thus obtaining one dimensional spatial light modulation from the LCD.



(a) (b)

Figure 13: (a) The weight pattern on the computer monitor (b) Oscilloscope trace of the detector output

C. Use as an Adaptive Wavefront Compensator

In a situation where a uniform amplitude wavefront is required, the LCD might be useful in compensating for amplitude differences. Consider a single mode laser with an amplitude wavefront function of G(x,y). The LCD can be made into a mask which transmits light according to some function B(x,y) such that for all x and y, B(x,y)*G(x,y)=A, where A is a constant and is less than or equal to the minimum value of G(x,y) since the LCD can only attenuate a signal. The apparatus might look like Figure 14. Hence, a non-uniform amplitude G(x,y) can be corrected to achieve a constant amplitude wavefront.

However, the pixel size of the LCD is a limiting factor on the resolution with which amplitude irregularities can be corrected. Furthermore, as mentioned earlier, each pixel is essentially a binary modulator. Hence, in order to increase the range of values for B(x,y) which can be accurately duplicated by the LCD, we need to look at a grouping of several pixels. For example, a 3x3 array of "binary" pixels could represent ten unique values for B(x,y). But resolution is lost when using groups of pixels rather than single pixels. Therefore, the LCD should prove useful for gross corrections to beam profiles, but may be insufficient to effectively make corrections to amplitude irregularities of smaller than approximately 1400 μm x 1200 μm.

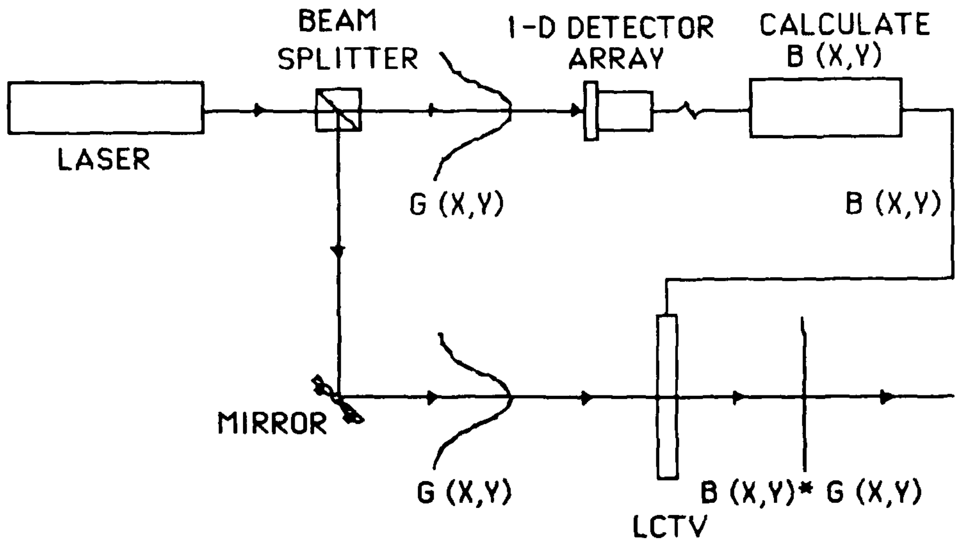


FIGURE 14: A proposed apparatus for using a LCD as an adaptive wavefront compensator.

VI. Conclusions

We have discussed our measurement of various operating parameters of the Radio Shack Liquid Crystal Television and we have presented several applications of the device in optical signal processing systems. The device was found to have a transmission peak of 30% at an applied voltage of 19.0 volts and a maximum modulation depth of 0.91 at a bias voltage of 14.6 volts. The LCD was also discovered to behave like a binary device, with perhaps only one intermediate grey level between the "on" and "off" states. The response time of the LCD is limited to input signals below 60 Hz. Additionally, a phase profile of the device demonstrates a three wavelength (830 nm) phase distortion over the face of the LCD. This distortion may be too large for certain phase critical applications. However, applications of the LCD as an amplitude filter are feasible. In particular, the LCD was found to have application as a 1-dimensional SLM in an adaptive optical signal processor. The Radio Shack Liquid Crystal Television was proven useful in the laboratory environment because of its low cost and because of its versatility as demonstrated in this report.

Appendix: Compensating for the Birefringence of the LCD

Consider a linearly polarized wave impinging on the face of the LCD. The birefringence of the liquid crystal material will cause this wave to split into two orthogonal components, termed the "ordinary" and the "extra-ordinary" axes, each with a characteristic index of refraction[7]. If the index of the extra-ordinary axis is larger than the index of the ordinary axis, the component along the extra-ordinary axis will propagate more slowly than the ordinary component. This differential delay results in an elliptically polarized beam at the output of the LCD.

With no bias voltage applied to the LCD, the input polarization will be rotated 90 degrees, as described in section II. Since the analyzing polarizer is parallel to the input polarization, one would expect to see no throughput. However, due to the birefringence of the liquid crystal, there is a non-zero component of the E-field that is still parallel to the polarization axis of the analyzer. This component limits the contrast achievable with the LCD.

In order to avoid this effect, we rotated the input polarization to be parallel to one of the birefringent axes. In so doing, the birefringent action of the LCD is minimized and the projection of the rotated linear polarization vector onto the polarization axis of the analyzing polarizer is reduced to zero. The optimal input polarization direction was determined as follows:

a. Set up the LCD without any bias voltage applied.
b. Rotate a halfwave plate in the beam path between the laser and the LCD.
c. Simultaneously adjust the waveplate and the analyzing polarizer until minimum throughput is obtained.

This allowed us to maximize the contrast of an LCD that had been prepared in accordance with the procedure on page 4.

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